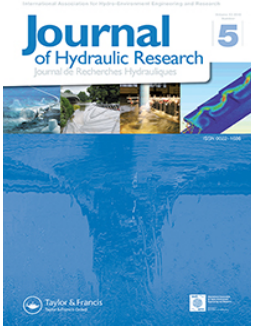

Journal of Hydraulic Research

ISSN: 0022-1686 (Print) 1814-2079 (Online) Journal homepage: http://www.tandfonline.com/loi/tjhr20

Hydraulics in the era of exponentially growing computing power

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Journal of Hydraulic Research Vol. 53, No. 5 (2015), pp. 547–560
http://dx.doi.org/10.1080/00221686.2015.1119210

Vision paper

Hydraulics in the era of exponentially growing computing power

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ABSTRACT
Recent advances in computational algorithms coupled with exponentially growing computing power pave the way for developing a powerful simulation-based engineering science framework for tackling a broad range of hydraulic engineering flows. Multi-physics simulations taking into account complex waterway bathymetry, energetic coherent structures, turbulence/sediment interactions and morphodynamics, free-surface effects and flow structure interaction phenomena are now well within reach and are beginning to impact engineering practice. I review such progress and offer specific examples highlighting the enormous potential of simulation-based engineering science to supplement and dramatically augment the insights that can be gained from physical experiments. I discuss major computational challenges that lie ahead but also underscore the enormous opportunities to take advantage of advanced algorithms, powerful supercomputers and big data to tackle societal challenges in restoration of aquatic environments, sustainable mitigation of the impacts of global environmental change, and development of efficient and environmentally compatible renewable energy systems.

Keywords: Complex hydraulic structures; data-driven models; energy–water nexus; flooding; large-eddy simulation; real-life waterways; sediment transport; simulation-based engineering science; turbulence

1 Introduction

In 2006 a US National Science Foundation blue ribbon panel (NSF Blue Ribbon Panel on Simulation-Based Engineering Science, 2006) introduced the term *simulation-based engineering science* (SBES) to recognize and draw attention to the enormous potential of computer simulation to revolutionize research in engineering and science in the twenty-first century. SBES can be defined as the discipline that provides the scientific and mathematical basis for the simulation of natural and engineered systems (NSF Blue Ribbon Panel on Simulation-Based Engineering Science, 2006). SBES takes advantage of rapid advances in the sophistication of multi-physics and multi-scale computational algorithms for solving systems of coupled nonlinear partial differential equations with complex boundary conditions, exponentially growing computing power, and the abundance of big data gathered from sensing systems across a wide range of scales to enable data-driven simulations of real-world problems at an unprecedented level of resolution and physical realism. SBES is thus a powerful tool of scientific discovery which supplements theory and experimentation to enable scientists and engineers to: (1) probe the physics of complex, real-life systems at a level of detail that is very difficult if not impossible to access by physical experiments alone; (2) conduct virtual experiments in cyber space to test hypotheses, evaluate and develop new theories, and quantify the uncertainty of computational predictions; and (3) revolutionize the design and optimization of real-life natural and engineered systems.

In the twenty-first century, hydraulic engineering has been playing an increasingly expanding role as a key discipline for tackling major societal challenges related to the sustainability of water resources and aquatic ecosystems, mitigation of the impacts of global environmental change, and the development of renewable energy systems. Examples include, among others, the development of sustainable stream, river and delta restoration strategies, managing the nitrogen cycle in aquatic environments, mitigating the impacts of extreme flooding events, and harvesting energy from tides, currents and waves. Predictive understanding of how turbulence interacts with sediment beds, energy-harvesting devices, fauna and flora and impacts the transport of nutrients and contaminants in real-life waterways is a critical prerequisite for developing science-based

Received 1 September 2015; accepted 6 November 2015/Open for discussion until 30 April 2016.

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ISSN 0022-1686 print/ISSN 1814-2079 online
http://www.tandfonline.com

solutions in all these areas. Given the enormous complexities of the underlying physical phenomena, SBES is often the only viable approach for tackling these challenges. Advancing a SBES framework for hydraulics, however, requires development of multi-scale and multi-physics, flow-structure interaction computational algorithms that are able to simulate flow phenomena in real-life waterways with natural (small-scale roughness, rocks, boulders, woody debris, vegetation, etc.) and engineered (e.g. hydraulic structures, energy harvesting devices, etc.) structures across the broad range of spatial and temporal scales. Major computational challenges stem from: (1) the arbitrary geometric complexity of waterways; (2) the fact that the boundaries of the flow domain are not static and are not known a priori but rather evolve continuously due to the coupled, non-linear interactions between turbulence in the water column, mobile sediment beds and the water-surface; (3) the presence of low frequency albeit highly energetic coherent structures that dominate aquatic turbulence; (4) flow/biota interactions and two-phase flow effects; and (5) the broad range of scales across which interactions occur, which range from a few seconds (temporally) and millimetres (spatially) for small-scale turbulent eddies to several days (temporally) and metres (spatially) for migrating bed forms. In a recent vision paper on large-eddy simulation (LES), Stoesser (2014) collectively referred to such challenges as the supergrid scale modelling challenge (i.e. developing models for real-life complexities that must be resolved on a given grid) to delineate them from the well-known subgrid modelling required for scales of turbulence that cannot be resolved by a LES on a given grid resolution. Stoesser pointed to the lack of predictive supergrid models as the major impediment for using LES to tackle practical hydraulic engineering problems in the foreseeable future. In this paper I will advocate that SBES powered by exponentially growing supercomputing is presently on the verge of ushering a new era in hydraulic engineering research; an era when practical hydraulic engineering flows can be simulated at unprecedented resolution with computational models that resolve energetic coherent structures and account for real-life multi-physics phenomena across scales.

The objective of this paper is not to present a thorough review of applications of LES and other turbulence models to hydraulic engineering flows as this has already been done in the excellent paper by Stoesser (2014) and a book by Rodi, Constantinescu, and Stoesser (2013). Rather, I will review very recent work, mainly from my group at the St. Anthony Falls Laboratory (SAFL), to highlight major advances in supergrid modelling that pave the way toward an exciting SBES future for hydraulic engineering and research. My motivation is to share with the community the underlying vision that has been guiding our work at SAFL for the last 10 years with the hope that the progress I will review herein will stimulate far-reaching advances in our field toward a future when SBES will radically transform hydraulic engineering research as we know it today.

The paper is organized as follows. First, I briefly describe key enabling advances in computational models. Subsequently, I present a few specific examples, spanning a range of complex hydraulic engineering and research applications, in which SBES coupled with experiments has been able to yield novel physical insights that could not have been gained by physical experiments alone. I also discuss applications in stream restoration and renewable energy systems to demonstrate the enormous potential of SBES as a powerful tool for tackling societal challenges in the energy/environment nexus. Finally, I discuss future challenges for further improving the physical realism of present day models and enabling them to take advantage of emerging exa-scale computing platforms to revolutionize hydraulic engineering research.

2 The St Anthony Falls Laboratory Virtual StreamLab

Over the last 10 years we have developed and extensively validated a multi-physics computational fluid dynamics framework with the vision to enable a SBES approach for complex hydraulic engineering and research problems. The computational framework, which is referred to as the Virtual StreamLab (VSL3D), is capable of carrying out multi-scale simulations of turbulence and transport phenomena in real-life natural waterways with embedded arbitrarily complex hydraulic structures and/or energy harvesting devices at an unprecedented level of resolution and realism. VSL3D employs a novel curvilinear immersed boundary approach (Kang, Lightbody, Hill, & Sotiropoulos, 2011) and can account for arbitrarily complex waterway bathymetry with embedded arbitrarily complex rigid (e.g. hydraulic structures) or dynamically evolving boundaries that interact with the flow in a fully coupled manner (e.g. the sediment–water and/or the air–water interfaces in rivers). Turbulence can be modelled with unsteady Reynolds-averaged Navier–Stokes (URANS) closure models or LES with the dynamic Smagorinsky model for subgrid-scale closure. Wall models are used to bridge the gap between the first fluid node and solid surfaces since for practical Reynolds numbers it is not feasible to resolve the near wall flow by placing grid nodes in the laminar sublayer (Kang et al., 2011; Kang & Sotiropoulos, 2011, 2012a).

VSL3D incorporates a two-phase flow formulation with level-sets to enable coupled simulations of free-surface effects in turbulent flows over arbitrarily complex bathymetry (Kang & Sotiropoulos, 2012b). Khosronejad and colleagues (Khosronejad, Kang, Borazjani, and Sotiropoulos, 2011, Khosronejad, Kang, & Sotiropoulos, 2012; Khosronejad, Hill, Kang, & Sotiropoulos, 2013) developed the coupled hydro-morphodynamic version of VSL3D and applied it to streambed erosion and scour under clear water conditions in curved open channels (Khosronejad et al., 2011), near bridge piers (Khosronejad et al., 2012) and in stream-restoration rock structures (Khosronejad et al., 2013; Khosronejad, Kozarek, & Sotiropoulos, 2014; Khosronejad, Kozarek, Palmsten, & Sotiropoulos, 2015a). The model was also extended to simulate sediment transport under live-bed conditions (Khosronejad & Sotiropoulos, 2014; Khosronejad et al., 2014, 2015a) and can efficiently simulate realistic bed forms across a range of scales, from centimetre-scale ripples in a laboratory flume (Khosronejad & Sotiropoulos, 2014) to the scale of 10s of metres with mega-dunes in large meandering rivers (Khosronejad et al., 2014, 2015a). A time-scale decomposition technique has been developed, enabling the use of time steps for the morphodynamic module up to one order of magnitude higher than for the flow, allowing the efficient simulation of dune migration over realistic flooding time scales (several weeks or months) (Khosronejad et al., 2014). The code is fully parallelized using message passing interface (MPI), and scales efficiently on thousands of CPUs.

VSL3D is routinely used today to carry out eddy-resolving simulations of complex hydraulic engineering flows on computational grids with hundreds of millions of grid nodes and on relatively modest (for today's standards) computational clusters (with few hundred processors). In what follows I will present a series of examples to illustrate how such a computational framework can be coupled with experiments and used as a powerful tool of scientific discovery. I will also highlight its potential as a tool for enabling site-specific hydraulic engineering design in stream and river restoration.

3 SBES as a tool of scientific discovery

3.1 *The structure of turbulence in field-scale streams*

VSL3D has been developed with the specific focus to enable data-driven high-fidelity simulations of turbulent flow and transport processes in real-life waterways. A critical prerequisite for realizing this vision was gaining access to good quality field measurements, which could be used to develop, validate and demonstrate the predictive capabilities of the model. For that we developed at SAFL the Outdoor StreamLab (OSL), a field-scale meandering stream laboratory facility with three meander bends and riffle/pool structure enabling field experiments under controlled laboratory conditions. The OSL is a 40 m by 20 m basin, which has been configured into a sand-bed meandering stream channel that is approximately 50 m long, 2 m wide, and 0.1 m deep at baseline flow. Native vegetation along with biodegradable coconut-fibre matting has been used to stabilize the streambanks. Entrance conditions for the OSL allow accurate control and measurement of water and sediment discharge rates, and the facility is outfitted with a sedimentation basin at its downstream end where sediment is collected and stockpiled for recirculation. Three-dimensional mean velocity and turbulence statistics measurements in the OSL are obtained using acoustic Doppler velocimetry (ADV) while the streambed bathymetry can me measured to sub-millimetre resolution using a laser distance sensor. For more details see Kang et al. (2011).

In our work the OSL and its virtual equivalent, VSL3D, have been integrated in a unique way not only to enable in-depth validation of the model, using detailed field measurements under well-defined conditions, but also to guide the experimental collection campaign using physical insights gained from the simulations. Such integration has yielded a series of novel insights into the structure of turbulence in meandering streams that could not have been obtained by using either approach alone. The scanned bathymetry of the OSL was used to reconstruct a virtual model of the stream using the CURVIB methodology in the VSL3D model. The computational grid (approximately 70 million grid nodes) was sufficiently fine to directly resolve roughness elements on the bed up to 10 cm in size – see Kang et al. (2011) and Kang and Sotiropoulos (2011) for details. LES and unsteady RANS simulations have been carried out on the same grid resolution under baseline and bank full flow conditions and many novel insights have been derived regarding the physics of turbulence in meandering streams (Kang & Sotiropoulos, 2011) and the uncertainties of numerical simulations associated with turbulence modelling errors (Kang & Sotiropoulos, 2012a).

One example illustrating the predictive power of the integrated OSL/VSL approach is shown in Fig. 1. LES for bankfull flow conditions revealed a striking pattern in the mean flow velocity field and turbulence kinetic energy (TKE) contours on the water surface. As seen in Fig. 1a, the entire surface flow emanating just upstream of the riffle is attracted toward a single line of convergence that is directing the surface flow toward the outer bank in the pool region. An elongated pocket of intense TKE production is also seen to emanate from the outer bank and coincide with the convergence line of the surface flow. To our knowledge this flow pattern had never been observed before experimentally and could not have been identified by the limited ADV velocity measurements used to validate VSL3D (Kang & Sotiropoulos, 2011). A detailed three-dimensional analysis of the LES flow fields showed that the line of convergence in Fig. 1b marks the location where two counter-rotating secondary flow cells collide on the water surface: (1) the curvature (or pressure) driven cell that is located near the inner bank, which rotates such that the surface flow is directed toward the outer bank; and (2) the turbulence anisotropy driven cell (van Balen et al., 2009; Blanckaert & Graf, 2001; Blanckaert, Duarte, & Schleiss, 2010; Blanckaert & de Vriend, 2003, 2004, 2010) that rotates in the opposite direction directing surface flow toward the inner bank (see Kang & Sotiropoulos (2011) for details). The point of collision of the two cells is an unstable saddle focus that undergoes low frequency lateral fluctuations causing the intense production of TKE observed in Fig. 1b. Armed with this new simulation-derived physical insight, a flow visualization experiment was carried out in the OSL by releasing paper pieces on the surface upstream of the riffle. As seen in Fig. 1c, all surface particles are indeed attracted toward a line of convergence as revealed by the LES. Note that the exact location of this line is a function of the relative strength of

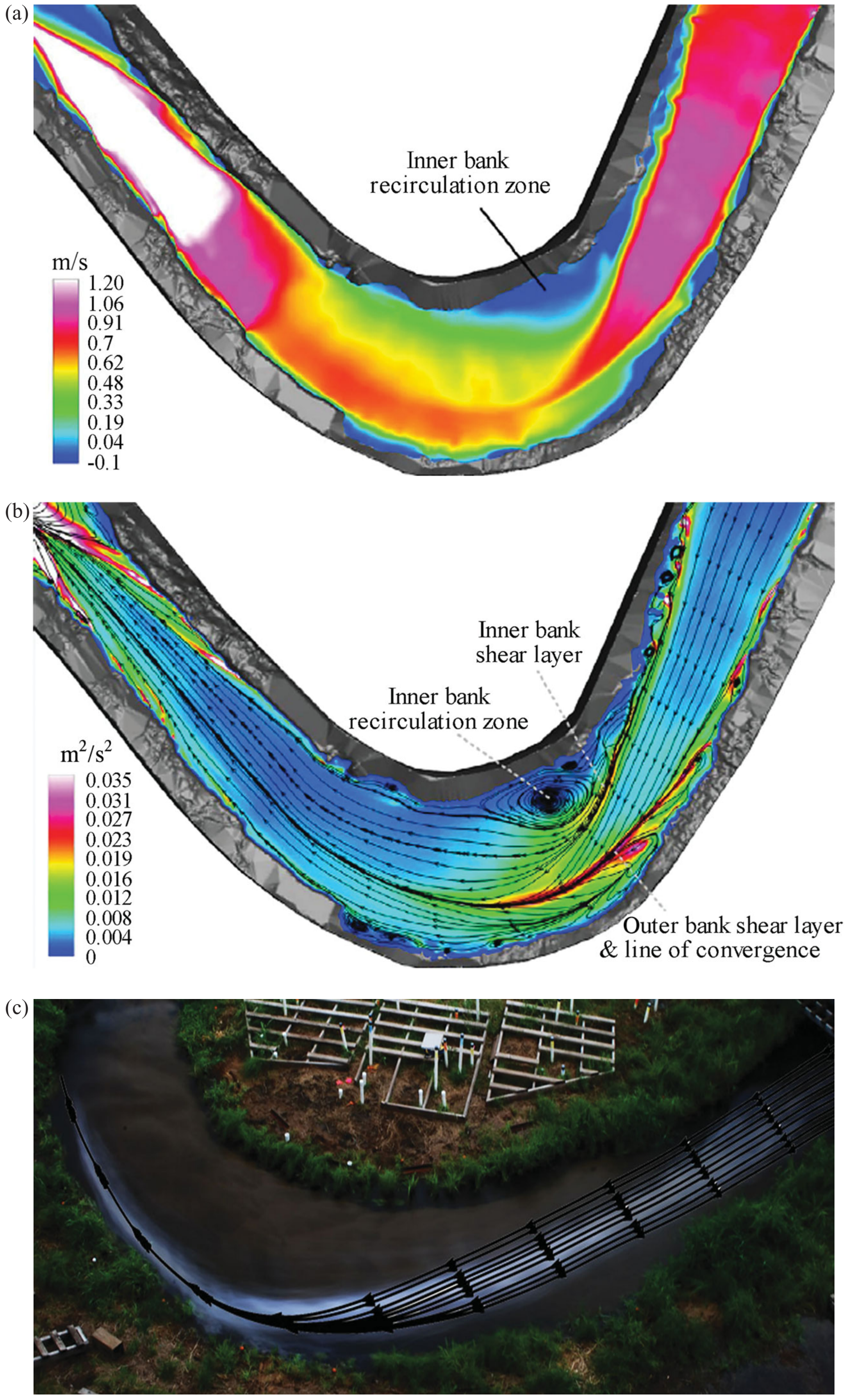


Figure 1 Simulated and observed flow patterns in the OSL: (a) simulated mean streamwise velocity; (b) simulated TKE contours along with mean limiting streamline at the water surface; and (c) over-exposed photograph of tracer particles released on the water surface of the OSL upstream of the riffle showing the converging streamlines (Kang & Sotiropoulos, 2012a)

the two secondary cells, which should depend on meander curvature, overall streambed bathymetry and inflow conditions. Therefore, this integrated OSL/VSL analysis uncovered a new feature of meandering streams with riffle and pool structure and suggested a simple flow visualization experiment that can provide insights about the 3D structure of the flow in real-life meandering streams. Namely, releasing passive tracers on the water surface can readily identify the line of convergence, which indicates the presence of the two cells and provides insights about their relative strength, marks the location of the channel thawleg, which coincides with the common flow of the two cells that is directed toward the bed, and identifies the region of intense TKE in the stream (Kang & Sotiropoulos, 2012a). Such an example serves to illustrate the predictive power of a SBES framework for meandering streams that can be used as a tool of scientific discovery and help guide experimental

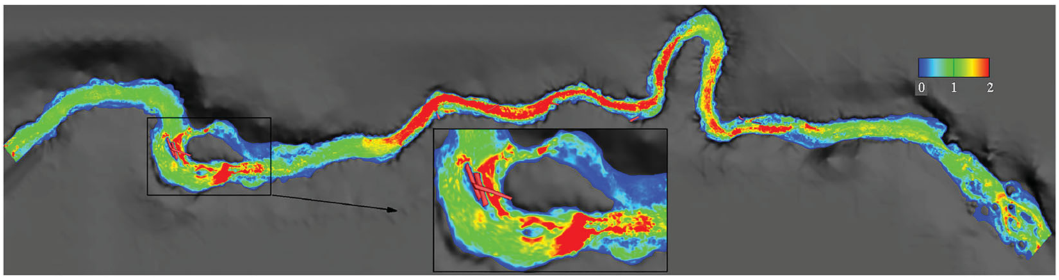


Figure 2 Snapshot of instantaneous velocity magnitude (non-dimensionalized with mean flow velocity ($= 0.16$ m s^{-1})) at the water surface of Eagle Creek, MN obtained with LES. Stream bed and banks are shown in grey and naturally fallen wood is shown in orange (Khosronejad et al., 2015b)

measurements to target regions of complex physics uncovered by the simulations.

The VSL3D model can now be used to carry out data-driven, high-fidelity simulations of turbulence in real-life field streams (Kang & Sotiropoulos, 2011; Morris, Mohammadi, Day, Hondzo, & Sotiropoulos, 2015). Figure 2 shows sample results from an application of the model to carry out a LES of turbulent flow and conservative solute transport through a headwater stream in Minnesota, located in the south Twin Cities metropolitan area. The detailed geometry of the stream reach, which is 135 m long, 2.5 m wide, and 0.15 m deep was surveyed and used as input to the computational model. The precise location and size of large woody debris was also surveyed and incorporated into the virtual model of the stream. The computational mesh is fine enough to resolve directly roughness elements on the bed up to 0.1 m size (see Khosronejad et al., 2015b for details). Being able to carry out simulations at such scale and fidelity opens up exciting opportunities for understanding how nutrients are processed in streams, how complex geomorphic features alter residence times and promote biogeochemical processes, and how various pollutants will be transported and mixed in any specific environment.

3.2 *Sand waves in open channels and waterways*

The capabilities of VSL3D to simulate scour and sand waves, from small-scale ripples to large dunes, in a variety of open channel flows with and without hydraulic structures have been demonstrated in a series of recent papers (Khosronejad & Sotiropoulos, 2014; Khosronejad et al., 2015a). Here I would like to highlight two specific examples, illustrating the predictive power of the model across a broad range of scales.

A major fundamental question in sand-bed morphodynamics has been the mechanism that destabilizes the initially flat bed and gives rise to organized bed forms (Chou & Fringer, 2010; Khosronejad & Sotiropoulos, 2014; Venditti & Church, 2005). There are two main hypotheses that have been put forth and debated in the literature: (1) a Kelvin–Helmoltz instability mechanism due to stratified flow effects in the vicinity of the sediment layer/water interface; and (2) sweep motions in the turbulent boundary layer that transport high momentum fluid near the bed and cause local increments in the fluctuating shear stress that give rise to local scour and deposition events (Khosronejad & Sotiropoulos, 2014). Previous computational studies of sand-bed morphodynamics have lacked the resolution to conclusively answer such questions (Chou & Fringer, 2010; Escauriaza & Sotiropoulos, 2011; Nabi, de Vriend, Mosselman, Sloff, & Shimizu, 2013). Venditti and Church (2005) carried out a series of very detailed experiments aiming to elucidate these questions and also provide datasets that can be used to validate computational models. Their experiment was carried out in a straight open channel with an initially flat sand bed and used high-resolution video recordings of the bed and image processing to systematically map its evolution from the initial deformation to the state of fully-developed three-dimensional transverse dunes at equilibrium. The results of Venditti and Church (2005) showed that initial bed deformation is characterized by the spontaneous onset of distinct cross-hatch marks that appear randomly throughout the bed.

Khosronejad and Sotiropoulos (2014) employed the morphodynamic version of the VSL3D to carry out a LES on a very fine computational mesh with near-wall resolution as fine as 20 wall units. The results of Khosronejad and Sotiropoulos (2014) reproduced the experimentally observed growth and long-term evolution of sand waves, from the initial spontaneous deformation of the sand bed in the form of cross-hatch patterns to equilibrium transverse dunes (Fig. 3). The computed cross-hatch features that appear on the bed at the early stages of bed evolution had length scales and overall orientation very similar to those observed experimentally. The availability of high-fidelity LES flow fields, however, enabled Khosronejad and Sotiropoulos (2014) to calculate the instantaneous footprints of turbulent sweep events on the bed and the patterns of the fluctuating wall shear stress and juxtapose them with the cross-hatch patterns on the sand bed. It was shown that the cross-hatch patterns essentially coincide with the footprints of sweep events. It was also shown that small pockets of fluctuating bed shear stress also develop at the nodes of the cross-hatch, and drive local micro-scour events and associated deposition. These results clearly give credence to the hypothesis that sweep events in the turbulent boundary layer are responsible for the spontaneous destabilization of the sand bed at the early stages of the process. To further explore the role of stratification effects, Khosronejad and Sotiropoulos (2014) carried out a numerical

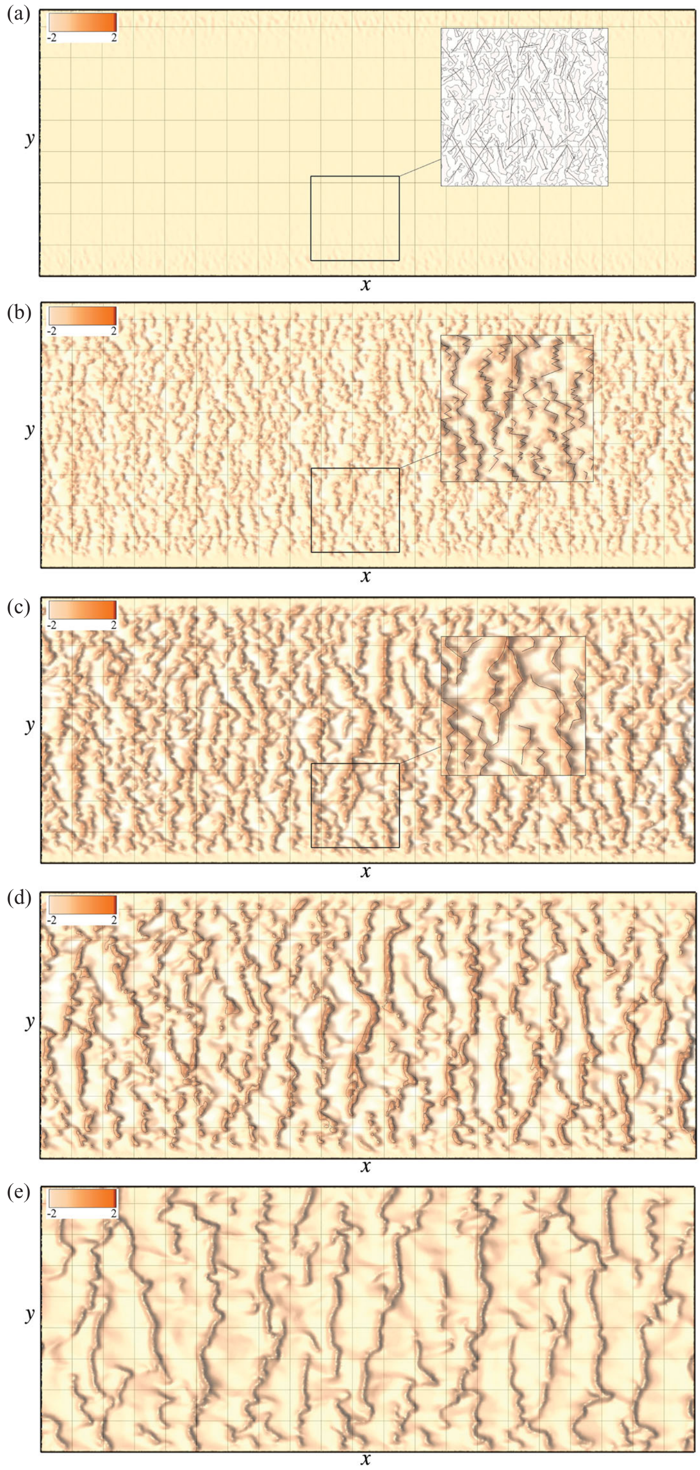


Figure 3 Simulated evolution of sand waves in a mobile channel starting from a flat bed at (a) $t = 5$ s, (b) $t = 50$ s, (c) $t = 100$ s, (d) $t = 150$ s, and (e) $t = 300$ s. Bed elevation contours are in cm. Flow is from left to right and the grid lines are 0.115 m apart along both directions (Khosronejad & Sotiropoulos, 2014)

experiment by repeating their simulations but with the buoyancy term in the Boussinesq form of the Navier–Stokes equations they solved in their model switched off – i.e. so eliminating the effects of stratification in momentum transport. They showed that the bed shapes emerging during the first 100 s of the process from the full model (with the buoyancy term activated) and the simplified (non-stratified) model were identical, thus, pointing to the conclusion that stratified flow instabilities are not important during the very early stages of bed instability. The results obtained by the two models diverged significantly at later times ($t > 100$ s) with the full (buoyancy term active) model giving results in very good agreement with the measurements. Therefore, these numerical experiments integrated with the high-quality experimental data of Venditti and Church

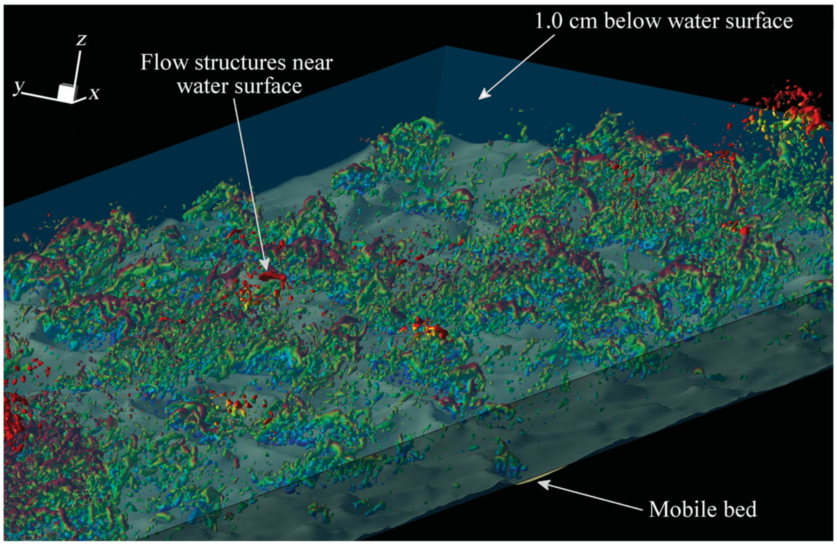


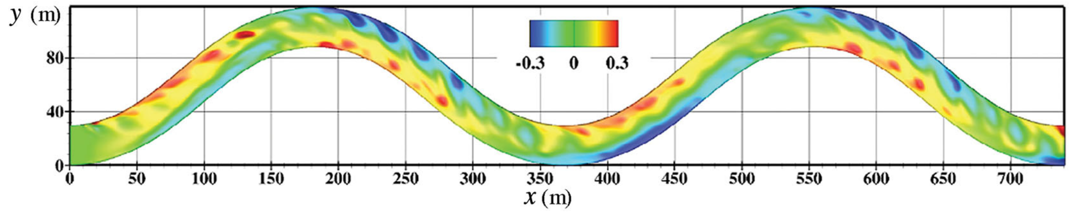
Figure 4 Snapshot of coherent flow structures over the sand waves and near the water surface. Body of water is shown in transparent blue. Flow is from left to right. For more details see Khosronejad and Sotiropoulos (2014)

(2005) clearly showed that essentially both hypotheses for the origin of bed forms are valid: turbulent sweeps dominate during the early stages of bed instability but stratification effects become important at later times when the layer of suspended sediment that forms above the bed as a result of sediment transport by near-wall coherent structures has grown sufficiently to start affecting the dynamics of the flow and the bed evolution. This is another clear example of how SBES can be a powerful tool of scientific discovery by dramatically augmenting the insights that can be gained from experiments alone. For a more extensive discussion of the sand waves and their impact on the flow, see Khosronejad and Sotiropoulos (2014). Here I note that these simulations yielded results in excellent qualitative and quantitative agreement with the experiments and provided many fundamental insights regarding the evolution of sand waves, from cross-hatch patterns to fully developed equilibrium transverse dunes, and their impact on the turbulent flow in the open channel. Figure 4 shows an instantaneous snapshot of the simulated bed-forms, the horseshoe-shaped coherent structures these dunes generate, and the footprints (surface boils) of these structures on the water surface. These findings confirm previous hypotheses derived from field observations (Best, 2005) as well as recent LES results over frozen dunes (Omidyeganeh & Piomelli, 2013a, 2013b). To our knowledge, however, these simulations represent the first comprehensive numerical simulation reproducing all stages of the coupled interaction of the turbulent flow in the water column with the initially flat sand bed; namely, from the initial cross-hatch indentations on the bed to fully grown equilibrium dunes inducing rich coherent structures that interact with the water surface.

The simulations discussed above required substantial computational resources since they were carried out on a very fine mesh ($\sim$ 80 million grid nodes) and used the same time-step for the LES and morphodynamic equations – i.e. the evolution of the flow and the bed were fully synchronized. This approach was undertaken because we wanted to maximize the fidelity of the simulations since the objective was to yield new fundamental insights into questions that have long been debated in the hydraulic and morphodynamic communities. Using this level of resolution to carry out simulations in streams and large rivers, however, is not practical. This is because turbulent eddies have scales of the order of few seconds while migrating bed forms often require many days to evolve. To address this challenge and enable simulations of bed forms in large rivers, Khosronejad et al. (2014) developed a dual time stepping approach, that can be used in conjunction with both LES and unsteady RANS turbulence models, allowing the use of a morphodynamic time step that can be significantly greater (e.g. one order of magnitude) than the time steps used to advance the hydrodynamic equations. Detailed discussion and systematic studies assessing the accuracy of this technique using experiments carried out in the SAFL OSL and available data in the literature can be found in Khosronejad et al. (2014, 2015a).

To illustrate the capabilities of VSL3D to simulate large dunes we show in Fig. 5a a snapshot of the results obtained from a coupled hydro-morphodynamic simulation, with the dual time-stepping technique and a URANS model for turbulence, of the morphodynamic evolution in a large meandering gravel-bed river (27 m wide and approximately 1 m deep). The results shown correspond to physical time of nearly two months and have been carried out on 160 CPUs for about 15 days of CPU clock-time. As discussed in detail in Khosronejad et al. (2015a) and also illustrated in Fig. 5b, the depositional patterns observed along the meander inner bend are strikingly similar to those observed in field photographs of large river systems (Dietrich, Day, & Parker, 1999). Moreover, simulations at such scale reproduce bed forms with statistical properties similar to those observed in nature (see Khosronejad et al., 2015a for details).

(a)



(b)

Figure 5 Large-scale dunes in field-scale rivers. (a) Colour map of instantaneous bed elevation (m) showing the geometry of the simulated dune waves in the G river in which the flow is from left to right (for more details see Khosronejad et al., 2015a); (b) field scale bed forms near the inner bend in a natural river in which the flow is from left to right (Dietrich et al., 1999)

4 SBES as a hydraulic engineering design tool

The predictive power of models such as the VSL3D executed on massively parallel computing platforms can now be brought to tackle challenging hydraulic engineering and research problems of major societal relevance. One such example is the area of stream and river restoration. Stream restoration projects typically involve the installation of in-stream structures, consisting of rocks (e.g. rock vanes, cross-vanes, J-hooks, etc.) or woody debris, at strategic locations within the stream with the aim to modify the structure of turbulence in the waterway to provide bank stabilization, maintain grade, or enhance in-stream habitat (Radspinner, Diplas, Lightbody, & Sotiropoulos, 2010). Existing guidelines for structure placement and spacing, however, are largely based on practitioner experience and intuition (Doll et al., 2003; MWCG, 2000; NRCS, 2007; Rosgen, 2006). Moreover, the efficacy of such guidelines has been evaluated by limited laboratory experiments in straight flumes (see reviews by Radspinner et al., 2010; Bhuiyan, Hey, and Wormleaton, 2010; Jamieson, Rennie, and Townsend, 2013) and field studies (Abad, Rhoads, Gneralp, & Garca, 2008; Miller & Kochel, 2010). An important shortcoming of in-stream structure design guidelines, therefore, is that they do not take into account the inherently site-specific interactions of turbulent flow, sediment transport, river bathymetry and structures that ultimately determine how the structures will perform at a given site, particularly when structures are installed to protect the outer bank of a meander bend from hydraulic erosion. As a result, failure of field installations of in-stream structures due to excessive erosion and other mechanisms is a rather common practitioner experience (Bhuiyan et al., 2010; Jamieson et al., 2013; Rosgen, 2006).

Given the site-specific geometric complexity and inherent three-dimensionality of flows in meandering rivers with in-stream structures, a SBES approach offers the only viable alternative for investigating the physics of such flows and developing physics-based design guidelines. An appropriate numerical model, however, would need to be able to resolve the complexity of the structures and river bathymetry and account for coupled hydro-morphodynamic processes and water-surface effects. The VSL3D model includes all these features (Khosronejad et al., 2015c, 2015d; Kang & Sotiropoulos, 2015a, 2015b) and we have used it to develop a SBES paradigm for developing physics-based design guidelines for rock structures in a range of river morphologies. Figure 6 illustrates the predictive capabilities of the level-set module of VSL3D, which has enabled us to carry out a high-fidelity LES of turbulent free-surface flow past a real-life cross-vane rock structure in an open channel (Kang & Sotiropoulos, 2015b). These simulations were able to capture very complex free-surface effects, such as local hydraulic jumps and surface waves, and reproduce both the mean and RMS of the measured water

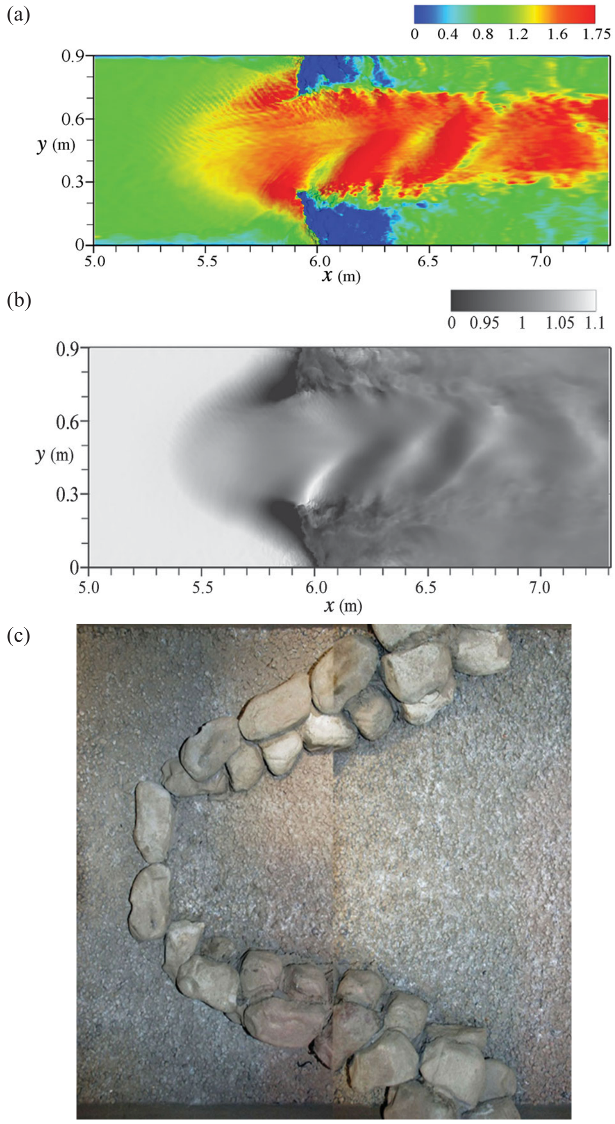


Figure 6 LES of two-phase free-surface flow over a real-life rock structure: (a) dimensionless streamwise velocity (non-dimensionalized with mean velocity) on the free-surface; (b) dimensionless flow depth (non-dimensionalized with mean flow depth) (Kang & Sotiropoulos, 2015b). Plan view of the experimental rock structures is shown in (c). Flow is from left to right

surface elevation with remarkable accuracy (Kang & Sotiropoulos, 2015b). Figure 7 presents results obtained from a URANS coupled hydro-morphodynamic simulation illustrating the ability of VSL3D to simulate the migration of large dunes (up to 1.5 m high) in a large meandering sand-bed river (30 m wide with a mean flow-depth of 1.35 m) with a J-hook rock structure mounted on the apex of one of the meanders. The results shown correspond to physical time of nearly nine days and have been carried out on 160 CPU's for about seven days of CPU clock-time (see Khosronejad et al., 2015a for more details).

We note that the VSL3D model is able to incorporate site-specific bathymetry and structure geometry data (Kang, Borazjani, Colby, & Sotiropoulos, 2012; Khosronejad et al., 2014, 2015a, 2015b, 2015c, 2015d) and as such it can be used to optimize structure placement for specific river geometry. In our work thus far, however, we have used the model to develop more general guidelines that are applicable to large classes of rivers in nature. For that, we have employed available data to construct two different virtual river systems representing typical sand and gravel-bed meandering rivers, and used them as test-beds for carrying numerical experiments, with the VSL3D in URANS mode, aimed at optimizing the spacing and placement of rock vanes by taking into account the complex physics of the coupled hydro-morphodynamic phenomena (Sotiropoulos & Diplas, 2014). For each of the two virtual river test-beds (sand and gravel beds) we begin by carrying out coupled hydro-morphodynamic simulations for the control case, i.e. the river without any structures in it. The results of these simulations are then used to gauge the effect of various rock vanes on river morphodynamics. For a given virtual river system, we start by embedding initially one rock structure and systematically vary parameters, such as number of structures, placement location, placement orientation, etc., to computationally explore their effects on structure performance and stability. Simulations are carried out over several meander bends and for several months of physical time at bankfull conditions to ensure that quasi-equilibrium has been established. For more details see Khosronejad et al. (2015c, 2015d) and Sotiropoulos and Diplas (2014).

5 Summary and future outlook

The computational advances I have briefly reviewed above demonstrate the enormous potential of SBES in hydraulic engineering research. Much of this progress has been enabled by the advent in computational hydraulics of immersed boundary methods (see Sotiropoulos and Yang, 2014), like the CURVIB method implemented in the VSL3D code, which provided an effective approach for building super-grid computational models (Stoesser, 2014) that can tackle the arbitrary geometric complexity of hydraulic engineering flows and address their inherent multi-physics and multi-scale complexities. Indeed immersed boundary methods are now being used with increasing frequency in computational hydraulic – I note in this regard the works of Giri and Shimizu (2006, 2007); Kara, Kara, Stoesser, and Sturm (2015); and Uhlmann (2005, 2008).

The key message that I hope to convey with this short vision paper is that numerical simulations of complex real-life hydraulic engineering flows in natural waterways, which up until few years ago were considered intractable in the foreseeable future, are now well within reach. Considering such advances in conjunction with the exponential growth in computational power, I will venture to predict that SBES is destined to radically transform hydraulic engineering research in years to come, enabling our field to play an even more influential role in tackling some of the most challenging issues confronting

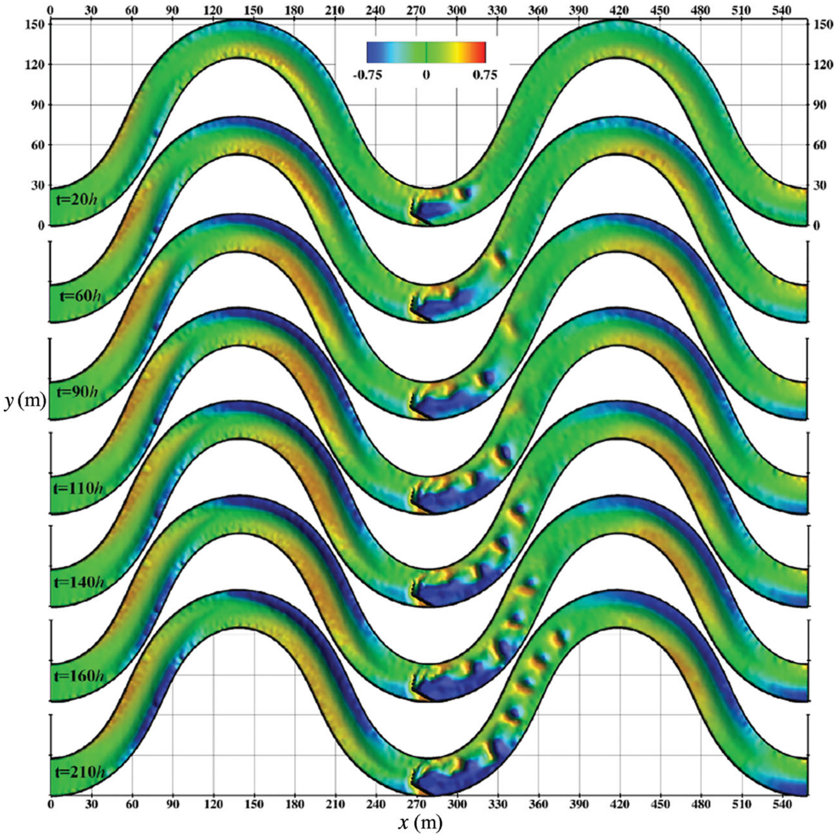


Figure 7 Colour maps of instantaneous bed elevation (m) from time instant $t = 20$ h (top) to $t = 210$ h (bottom) showing the geometry of the simulated dune in a sand bed river with a 30° J-hook vane installed at the apex of the middle meander. Flow in all pictures is from left to right (Khosronejad et al., 2015a)

humanity in its quest for a sustainable future. For example, integrating predictive computational models such as those I reviewed above, with data from satellites, LiDARs and robotically deployed sensors in waterways will open up exciting opportunities for developing predictive, site-specific models of inland and coastal flooding of unprecedented realism and resolution. Such models will enable engineers, practitioners and stakeholders to create in cyberspace virtual extreme flooding events, understand their potential impact to communities, infrastructure and economic development, and develop effective flood protection and mitigation strategies to address the impacts of global environmental change.

A glimpse into such a future is provided in Fig. 8, which shows a LES of turbulent flow and morphodynamics through a 3 km stretch of the Mississippi River where it meets with the interstate highway I-694 under two flow conditions: base flow and 100 year flood event. The Minnesota Department of Transportation (MNDOT) recently commissioned a study at SAFL to computationally investigate the impact of a 100 and 500-year flooding events on the I-694 bridge piers. Stitching together LiDAR data with detailed bathymetric surveys of the River reach we generated a high-resolution digital elevation model (DEM) and used it to carry out a LES of the turbulent flow and sediment transport under baseline and extreme flooding conditions. Field measurements under baseline conditions were collected and used to validate the model but the simulations are presently being used as a tool to understand how the bridge piers will respond (e.g. maximum scour depth and dynamics of scour due to passage of bed forms) to such extreme flooding events. Simulations like this and at even bigger scale and scope are bound to become routine in years to come and start impacting decisions made by agencies, stakeholders and their consultants. Such simulations may not only be used to assess impacts of extreme flooding events but also to develop science-based, site-specific strategies to restore streams and rivers, to predict scalar (e.g. temperature) and contaminant transport and their impact to ecosystems, to understand biogeochemical processes and their connections to local hydraulic conditions, and to manage nitrogen transport and processing in waterways.

Another major societal area where SBES will enable hydraulics to make a major impact is the so-called nexus of water and energy. Marine and hydrokinetic (MHK) energy – including wave, tidal and river technologies – is an emerging source of renewable energy that is aggressively being developed in many places around the globe. According to the *2011 US Marine and Hydrokinetic Energy Roadmap* (OREC, 2011), untapped MHK energy resources in the USA have the potential to provide up to 10% of the nation's electricity, more than the amount of electricity produced by all conventional hydropower in the country. Achieving this goal, however,

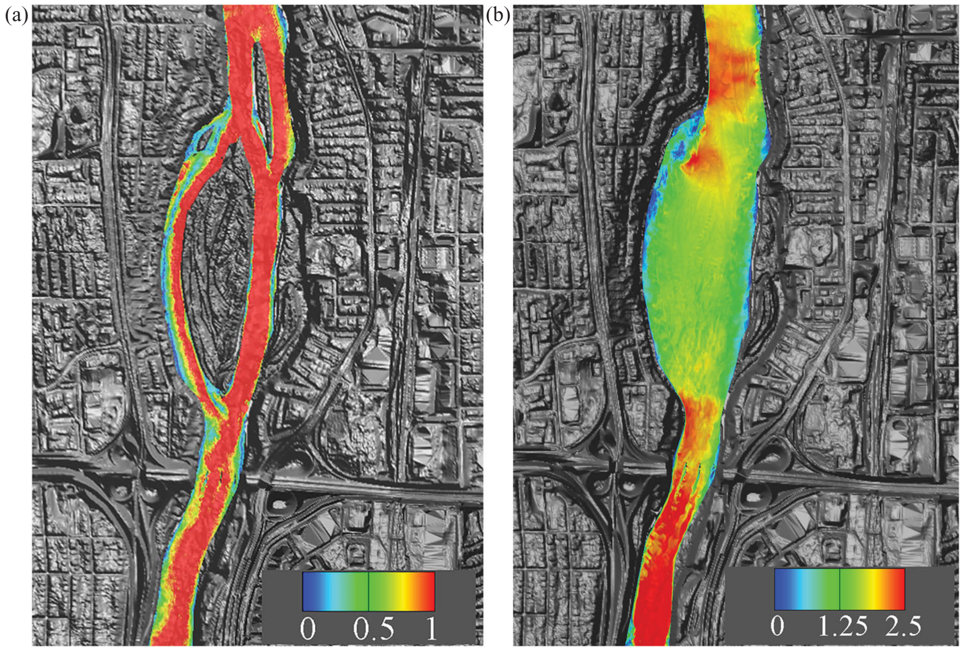


Figure 8 Coupled hydrodynamics and morphodynamics LES of turbulent flow through a 3.5 km reach of the Mississippi River where it intersects with Interstate I-694 in Minnesota, USA: (a) base flow; and (b) 100 year flood conditions. Contours of simulated velocity magnitude are in m s^{-1} and flow is from top to bottom

requires developing a predictive understanding of how energy extracting devices (e.g. turbines and wave energy converters) will perform in multi-device arrays embedded in real-life waterways with complex bathymetry, energetic coherent structures, free-surface and waves (for wave energy converters) and mobile sediment beds (Kang, Yang, & Sotiropoulos, 2014). A SBES framework that is capable of simulating river, tidal and ocean current turbines and wave energy converters (WEC), is applicable from the scale of a single device up to the scale of large multi-device arrays, and can incorporate site-specific bathymetry effects and wave environments, sediment transport, and device-flow-wave interactions, can be a powerful tool for augmenting the innovation capacity of the nascent MHK industry. An example of the potential predictive power and overall promise of such a framework is shown in Fig. 9, which illustrates the application of the VSL3D model to simulate the interaction of two tidal turbines with a mobile sediment bed under clear water scour (Yang et al., 2015).

While I am very optimistic and enthusiastic about the future role of SBES in hydraulics, I do not advocate that such computing capability will eliminate the role for physical experiments. To the contrary, the resolution and level of detail that will be required from experimentalists will even increase in order to catch up with the predictive capabilities of a SBES framework, help quantify its uncertainties, and develop confidence that such a framework can be used to design hydraulic engineering systems and make decisions. In fact, SBES and physical experiments must be closely intertwined to realize the full predictive power of computational modelling at such scale. Validating the models with relevant experimental measurements for the phenomena of interest in a given application will allow

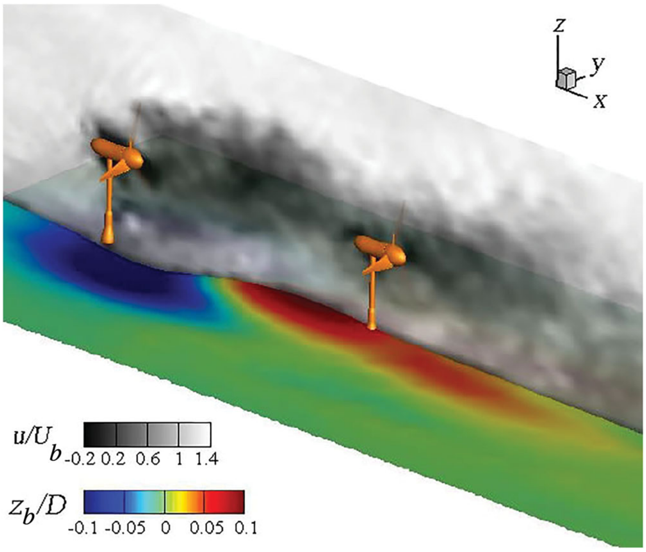


Figure 9 Coupled hydro-morphodynamic LES of turbulent flow past two hydrokinetic turbines mounted on a sand-bed open channel. Grey contours show instantaneous velocity magnitude (u) (non-dimensionalized with bulk velocity (U_b)) in the water column on a vertical plane. Colour contours show the bed elevation (z_b) (non-dimensionalized with rotor diameter (D)) revealing complex regions of scour and deposition around the turbines. Flow is from left to right (Yang et al., 2015)

SBES to be used as a predictive tool of scientific discovery enabling engineers to conduct virtual experiments and realize hypothetical future scenarios, which cannot possibly be realized in an experiment (e.g. the effect of a 500 year flood on a specific bridge deck in a specific river).

Even though much progress has already been achieved, major research advances need to be realized in the coming years to reap the full benefits of SBES for hydraulic engineering. Efficiently tackling the large disparity of scales in waterways (e.g. from the scale of a tidal estuary to the scale of MHK turbine) requires development of adaptive and locally refined grids that will enable multi-scale and multi-resolution simulations of turbulence in waterways. Efficient fluid–structure interaction computational algorithms are needed for simulating energy harvesting devices interacting with flow, waves and sediments in waterways and coastal areas as well as for modelling interactions of turbulence with vegetation and biota. New sediment transport parameterizations are needed to take advantage of the advances in hydrodynamic models that can now resolve energetic coherent structures interacting with sediment beds. Along the same lines, sediment models need to incorporate the effects of multiple classes and types of material as well as the effects of cohesive sediments. And last but not least, such an SBES framework needs to be structured to take full advantage of peta-scale and emerging exa-scale computing platforms. This requires cross-disciplinary interactions between hydraulic modellers and computer scientists to develop computational codes that are aware of and tailored to the architecture of emerging extreme scale computing platforms so that the codes can scale efficiently in millions of computing cores – an undertaking which is far from trivial. I am fully aware that the vision I have laid out herein constitutes a grand-challenge scale undertaking. However, I am optimistic that a SBES-dominated hydraulic engineering future is just around the corner and will be realized within the next decade or even sooner, forever transforming our field.

Acknowledgements

I would like to acknowledge the contributions of my past and current students and postdoctoral associates with whom I had the pleasure to work with during the last 10 years at the SAFL. Special thanks to Ali Khosronejad, Xiaolei Yang, Seokkoo Kang, Toni Calderer, Iman Borazjani, Lian Ge and Anvar Gilmanov who have made major contributions in the development of the computational tools that have enabled us to carry out the simulations I reviewed in this paper.

Funding

This work was supported by the National Science Foundation (NSF) [PFI grant IIP-1318201], the Minnesota Department of transportation (MnDOT), the National Cooperative for Highway Research Program (NCHRP), and the Initiative for Renewable Energy and the Environment (IREE) at the University of Minnesota.

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